National Aeronautics and Space Administration

Terminal Guidance Navigation for an Asteroid Impactor Spacecraft

Shyam Bhaskaran

Jet Propulsion Laboratory

California Institute of Technology

Introduction

- On July 4, 2005, the Deep Impact impactor spacecraft successfully collided with comet 9P/Tempel 1, while the main spacecraft flew by and shuttered images which captured the impact
  - 1st hypervelocity impact of a primitive Solar System body
  - Not primary goal of mission, but it did demonstrate that such an impact could be accomplished with current technologies and relatively modest budget
- For relatively small asteroids and short turnaround times from detection to impact, kinetic energy technique recommended as the most practical and cost effective technique for deflection

AutoNav

- DI impact made possible by onboard closed-loop autonomous navigation system (AutoNav) for the terminal guidance
- AutoNav originally developed as a technology demonstration on Deep Space 1
- To date, 5 missions, using 4 different spacecraft, have used AutoNav, primarily to impact a comet nucleus (DI), and to track asteroid or comet nucleus through closest approach for a flyby
  - Deep Space 1 (cruise and flyby of comet Borrelly)
  - Stardust (flyby of asteroid Annefrank and comet Wild 2)
  - Deep Impact (Impactor and Flyby spacecraft imaging for comet Tempel 1)
  - EPOXI (flyby of comet Hartley 2)
  - Stardust NExT (flyby of comet Tempel 1)
- Technology for tracking nucleus through flyby identical to that needed for closed loop control for flyby

Comparison of AutoNav Approach Parameters for Past Missions and Potential Impactor Mission

Mission/Target	Flyby Radius (km)	Flyby Velocity (km/s)	Approach Phase (deg)	Target size (km)
DS1/Borrelly	2171	16.6	65	4.8
STARDUST/Annefrank	3076	7.2	150	4.8
STARDUST/Wild 2	237	6.1	72	4.0
DI/Tempel 1	500/0	10.2	62	6.0
EPOXI/Hartley 2	694	12.3	86	1.6
STARDUST NExT/Tempel 1	182	10.9	82	6.0
Potential KI Scenarios	0	~3 to 20	~60 - 140	~0.100 – 0.300

Brief Background on Deep Space Navigation

- Step 1: design trajectory to intercept asteroid to satisfy mission constraints
  - Launch vehicle
  - Delivered mass
  - Fuel required
  - Approach velocity, phase angle
- Step 2: navigate reference trajectory from launch to impact
  - Standard techniques of ground-based navigation used for launch, cruise, and early approach, using primarily radiometric tracking data
  - Ground navigation delivers spacecraft to interface location at predetermined time before impact, at which time light-time delays require that onboard control take over
  - For previous missions, this point ranged between 30 min and 2 hours prior to closest approach/impact

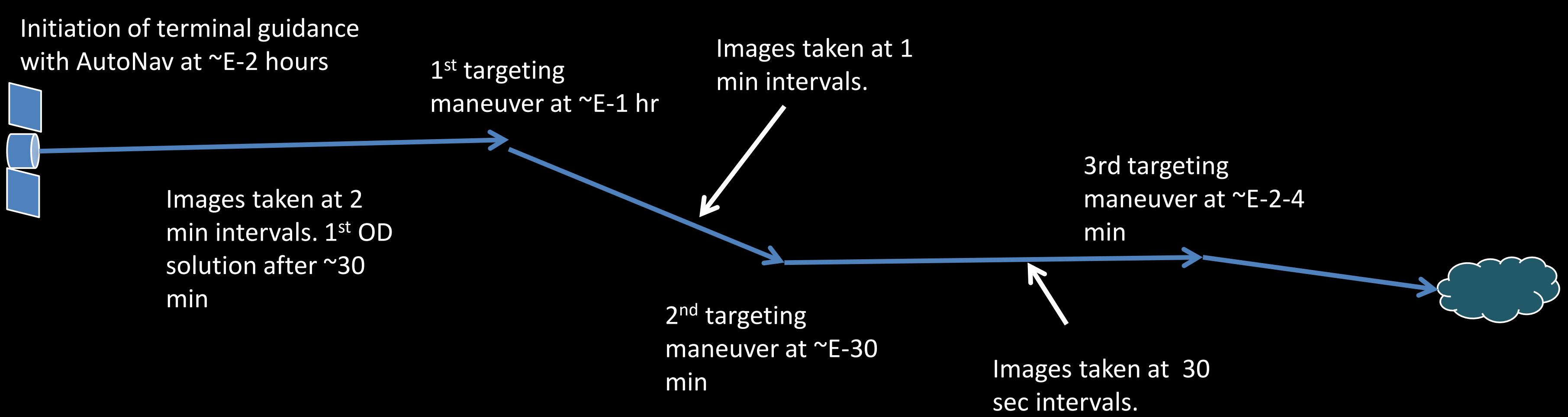
AutoNav Description

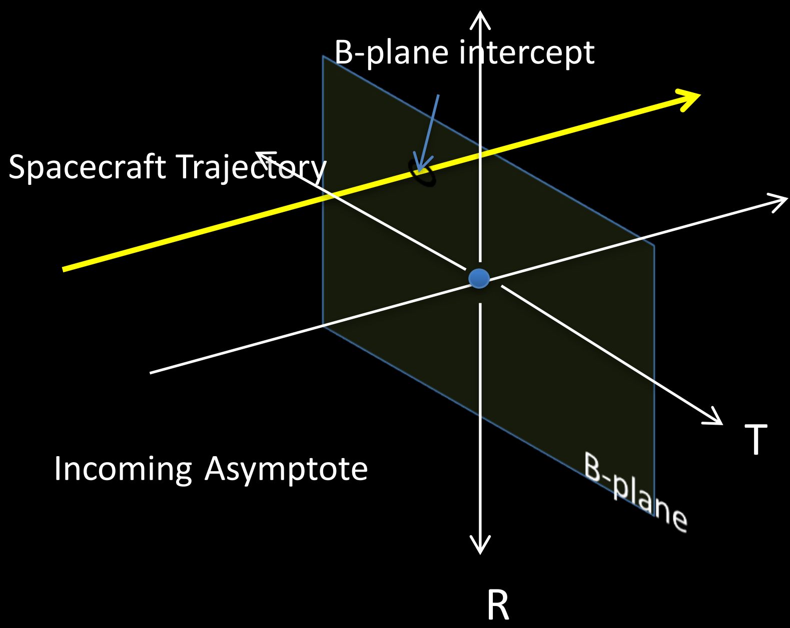
- Entirely self-contained system uses onboard camera to take images of target body to compute target relative navigation solution
  - Does not require radio link to other s/c or the Earth
- 3 main components of AutoNav
  - Image processing element to extract target center-of-figure information
  - Orbit determination element to combine set of target centroid information in least-squares filter estimate of s/c trajectory
  - Maneuver planning and execution element to compute delta-V needed to hit target
    - For Deep Impact, 3 maneuvers were used for targeting. These were placed at E-90 min, E-35 min, and E-12.5 min

Some Notes on Onboard Orbit Estimation

- Different from “follow the target” techniques using PN guidance in that the complete relative orbit solution is estimated
- AutoNav needed to be robust against various failure modes
  - Failure of camera during any portion of terminal guidance
  - Loss of images due to corruption from stray light, cosmic rays, etc.
  - Large variations in COB due to shape/phase effects
  - Attitude disruptions due to particle impacts (for comets)
  - Unknown size, brightness, shape, orientation of target object
  - Failure of TCM to execute

Notional Targeting Scenario for KI





Optical Navigation (Opnav)

- Opnav images provided by onboard camera
- Provides only target-relative navigation information (ground-based radiometric data provides Earth-referenced navigation information)
- Key parameters for camera include IFOV (angular resolution of single pixel), sensitivity
  - These, along with Vinf and approach phase, determine when target object becomes resolved, accuracy of measurement, earliest detection, and ability to see stars along with object to provide inertial reference for observations
- Note that for the deflection scenarios we are examining, the target object will almost always be unresolved at start of terminal guidance, and may remain so until < 5 minutes to impact
- Prior observations of target body, either by orbiting or earlier flyby, can dramatically improve Opnav performance since characteristics of body (shape, size, orientation) will be known

Attitude Knowledge

- Errors in attitude knowledge directly affects accuracy of OD
  - Must estimate attitude error as part of filter which degrades strength of target relative angular information
- "Stellar mode" attitude knowledge
  - Stars available in navigation camera, attitude knowledge near perfect
- Star tracker/IMU
  - Degraded attitude knowledge depending on Star tracker/IMU information
  - Past experience suggests using IMU propagation only
    - IMU bias and drift primary source of error for terminal guidance because these can be difficult to separate from translational motion
  - 2 general classes of IMU capability needed for KI (MIMU, SSIRU)
    - Less capable IMUs (e.g., LN 200) not good enough for this purpose

Monte Carlo Simulations

- Impactor targeting accuracy assessed through Monte Carlo simulations
  - Confidence in simulations have increased with comparison against actual flight performance
  - Thus far, flight performance has fallen within envelope of simulated cases
- Previous studies* looked at KI performance across a range of scenarios
- Targeted trade studies can be done for specific missions to assess performance for a range of parameters
  - Camera specifications (focal length, sensitivity, frame rate)
  - Image processing settings
  - Spacecraft attitude control/knowledge requirements
  - Spacecraft thruster performance
  - Orbit determination filter tuning
- A quick set of simulations were run for the PDC 2017 KI scenario
  - Results very preliminary – no time to tune filter, adjust parameters, etc.

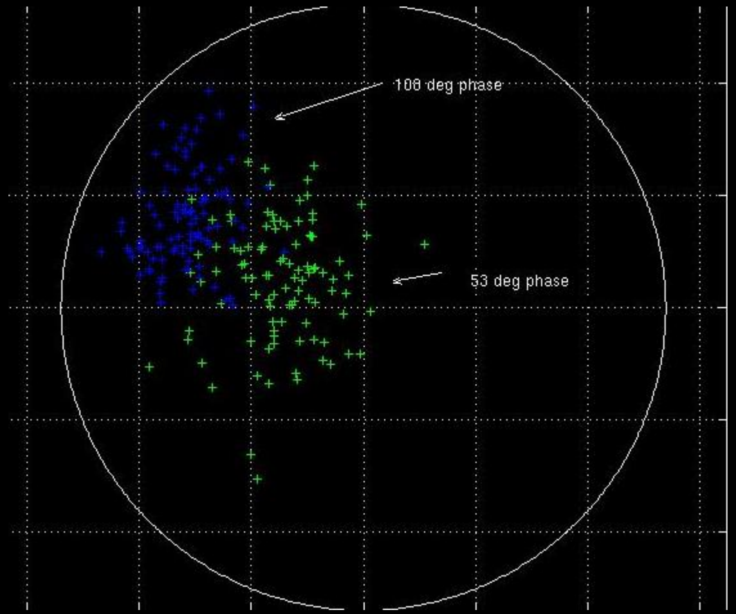
* Bhaskaran, S., Kennedy, B., "Closed loop terminal guidance navigation for a kinetic impactor spacecraft", *Acta Astronautica*, 103, (2014), pp. 322-332

Simulation Results (from Bhaskaran, Kennedy, 2014 study)

Case	**Vinf (km/s)**	**Phase angle (deg)**	**Stellar reference**		**SSIRU**	
			100 m	300 m	100 m	300 m
1	7.5	30	98.8%	100.0%	85.5%	100.0%
2	7.5	80	96.5%	100.0%	73.8%	99.2%
3	12.5	140	56.6%	99.4%	53.8%	90.6%
4	20	5	100.0%	100.0%	75.4%	99.6%

Simulation Results (2017 PDC Scenario Case)

- Two cases looked at
  - Vinf = 15 km/s, Phase angle = 53 deg
  - Vinf = 12.7 km/s, Phase angle = 108 deg
- 3 attitude modes
  - Stellar reference (near perfect attitude knowledge
  - SSIRU class gyro
  - MIMU class gyro



Case	Vinf (km/s)	Phase angle (deg)	Stellar reference	SSIRU	MIMU
1	15.0	53	100%	100%	38%
2	12.7	108	100%	100%	38%

Conclusion

- Attitude knowledge mode is the single biggest factor in determining impact success
  - With stellar reference, probability of success fairly high
  - Otherwise, must have very stable IMU
- Phase angle second largest effect
  - High value in designing reference trajectories which lower approach phase angle
- Precursor mission valuable for increasing chance of success
  - Can correct for COB, phase angle effects
  - Minimize sizes of maneuvers needed to remove larger target body ephemeris errors

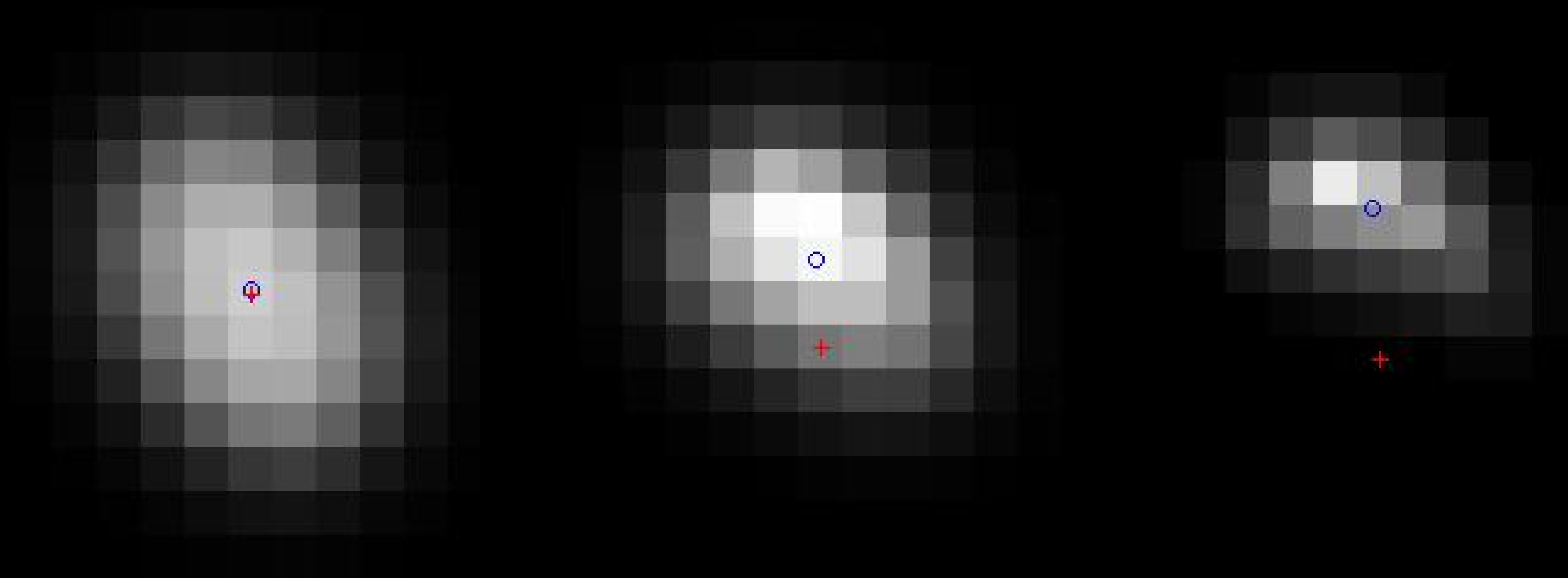
Backup

Simulation Parameters

Initial asteroid-relative state error	Position: 30 km Velocity: 5 cm/s
Gates model maneuver execution error	Fixed magnitude: 4.3 mm/s Proportional magnitude: 10% Fixed direction: 4 mm/s Proportional direction: 3.1%
Gyro errors (MIMU class)	Rate bias: 0.005 deg Angle random walk: 0.005 deg/sqrt(hr)
Gyro errors (SSIRU class)	Rate bias: 0.0005 deg Angle random walk: 0.0005 deg/sqrt(hr)
Asteroid size	130 x 90 x 90 m 390 x 260 x 260 m
Asteroid pole orientation	RA: 0 to 360 deg, uniform Dec: -90 to 90 deg, uniform

All errors values are 1 sigma unless otherwise noted

Example of Phase Effects in Final Image



Phase = 5 deg

Phase = 80 deg

Phase = 140 deg